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Procedia CIRP 17 (2014) 535 – 540

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Variety Management in Manufacturing. Proceedings of the 47th CIRP Conference on Manufacturing Systems

Handling hazardous part variety: Metalcasting as a case point

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Abstract

Robot grippers are employed to handle parts in automated assembly operations. In conventional foundry assembly, such grippers are dedicated to large volume production of standard parts. However, due to varying customer preferences in the recent years of increased global competition, the foundry industry needs to cope with rapid market changes by increasingly relying on flexible automated assembly lines which are capable of handling a wide variety of parts in small to medium volume and variety. These flexible automated lines require flexible grippers to handle parts which are otherwise not safe to be handled by human operators. This paper discusses various handling methods for hazardous foundry parts. The paper presents an extensive literature review for handling such cast parts and sand cores and their respective shortcomings dependent on the delivery methods. Four versions of grippers developed and implemented for handling cast part variety at the case company have been presented.

Selection and peer-review under responsibility of the International Scientific Committee of "The 47th CIRP Conference on Manufacturing Systems" in the person of the Conference Chair Professor Hoda ElMaraghy"

Keywords: Automation, Hazardous Part Handling, Gripping

1. Main text

In the factory of the future, it would be only possible to meet the market demands by means of flexible designs for automation equipment. In the 21st century, under the influences of globalization, manufacturing companies are required to meet continuously changing demands in terms of product volume, variety and rapid response. In order to fully realize the benefits of flexible automation, the grippers, being one of the few direct contacts with the product at the very bottom of the manufacturing chain, must be designed for flexibility. Evaluation of certain parameters directly in the gripper can expedite processes thereby reducing overall manufacturing costs.

The use of robots in foundries for supporting flexible automation is certainly not a recent development. Robotics has been identified by the foundry players as essential for winning new customers. The anticipated benefits of application of flexible automation, namely, improved worker safety, and higher quality castings dates back to the first such recorded application in die casting in 1961 at Ford Motor Company in the US. Robot grippers are links between the manipulators and handled object the capabilities of the gripper is an essential factor for economic effectiveness of automatic handling systems.[1] The cost of grippers may be as high as 20% of a robot's cost, depending on the application and part complexity. [2] In spite of their initial capital and ongoing maintenance expenses, robot-gripper systems are found to be effective for repetitive material handling functions, because of their reliability, endurance and productivity. Research in the area of robot grippers for handling solid parts has two main directions. Researchers following the first direction try to develop methods and techniques to automate the design and selection of robot grippers for a given industrial use. The second direction is influenced by the fact that the application of grippers is task-specific. Researchers adopting this approach attempt to create cost effective specific grippers to automate specific processes or versatile grippers for a wide range of applications. The latter direction constitutes the basis of the work presented in this paper. Industrial gripppers were

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doi:10.1016/j.procir.2014.02.030

developed and tested at participating SME for handling hazardous parts. A hazardous part was defined by the stakeholders as a casted part (weighing > 20kgs) with sharp metal flash on the edges which make them unsuitable for human handling due to its physical and metallurgical properties.

Wright compared the grippers to the human grasping system, and categorized the design requirements of grippers into (a) compatibility with the robot arm and controller, (b) secure grasping and holding of the objects, and (c) accurate completion of the handling task. [3] Many industrial examples of grippers were also described, and the guidelines for gripper design were presented. Pham et al. summarized the strategies for design and selection of grippers in different application cases.[2] They have suggested strategies to achieve flexible and cost effective gripping such as notching of gripper fingers, changing of gripper fingers [4], changing of grippers, use of multiple gripper units [5] and the use of passive [6] and active [7][8] universal grippers. Most of the universal grippers have three fingers, which is the number required to achieve 90% of the flexibility possessed by a five fingered hand. [9]

It is based on the hazard cast part automation needs identified by the participating foundry that the related study was carried out described shortly. The rest of the paper is organized as follows: following an extensive literature review and discussion about applicability and limitations on different grippers that are suitable to handling sand cast parts, four versions of part handling solutions developed for implementation at the participating foundy are described along with the integration of the gripper in a finishing cell. The details on the implemented gripper is limited due to confidentiality. Finally, a summary and future directions of research is provided.

2. Industrial Challenge

The use of robots in die casting have been in pouring metal, parts integrity checking, cooling of parts, trimming, storage, die insertion and die lubrication operations. Much of the automotive industry is switching to aluminum parts because of their light weight and energy efficiency requirements. The aluminum foundries are used to cast automotive parts like chassis components, wheels and other complex thinner profile parts. Robots play a crucial role in aluminum foundries as well enabling part quality and consistency. Few robot applications have been reported for sand casting foundries. The robots in such foundries can be used for handling sand cores, part insertion in casting dies, part deburring and part handling, hence enabling foundry flexibility. New plants and large scale modernization of existing foundry plants will increasingly be driven by high degree of robotic automation. This would enable the automated foundries of tomorrow be outstanding in both quality of their products and the cost efficiency of their manufacturing. [10]

Foundry SMEs in particular are in need help from automation technology, and some of the reasons are listed below

1. Intensive in manual labour
2. Have high variation in parts, due to variables such as temperature of molten metal, metal solidification defects etc. which is a huge detriment to automation
3. The extreme environmental working conditions of foundries raising health and safety issues necessitates the need for automation

From above we notice that the first and third reasons are the main drivers supporting the need of automation in foundries. The second reason is a deterrent to automation implementation. Global competitive pressures, along with increased demand from major customers are the two primary factors fueling the need for automation of casting facilities.

Most of the published literature in flexible foundry automation is commercial and there is limited research and academic literature in the area to help foundries establish tools to promote competitiveness in automation. [11][12][13] The need of research literature in foundry automation was also confirmed by the American Foundry Society. From a literature perspective, Barnett presented the trends in automation in precision investment casting with a case study at P.I. Castings. [14] Hudak presented an industrial review of diecasting and highlighted the need for automation and part handling. [15] Ribiero et al. developed a methodology for benchmarking the Portuguese metalcasting consortium (eight foundries), to promote business cooperation within the industry and enlarge available business information.[16] This study only focused on developing a performance measurement framework, and identified developing manufacturing flexibility as a critical factor for measuring innovation in manufacturing. Spangler et al. published results proposing manufacturing performance measurement tools related to the metalcasting industry in the US based on the needs identified by the Defense Logistics Agency (DLA).[17] Separate questionnaires developed for the sand casting, die casting and investment casting suppliers are mailed to the 283 foundries listed with the American Foundrymen's Society (AFS) foundry database. The researchers received 39 completed surveys which are used to develop guidelines and perform further analysis to identify relationships between variables for the DoD and DLA. Vedel-Smith et al. presented a methodology for enabling traceability cast iron foundries by part number marking on individual castings. [18] Arabatzis et al. described the issue of traceability in aluminium foundry.[19]

The participating foundry wanted to wanted to look into automating the CNC finishing and thereby reducing the manual handling of heavy parts with flash on its edges.


Fig. 1. Cast iron part with flash on the edges (left); Cast part weighing >35kgs with profile and flash (right)

The cast iron parts had weight ranging from 20-35 kg and had with sharp metallic edges. The grippers needed to automate the handling of the part variety had the requirement of being integrated with commercial manipulators (such as ABB IRB6400), be compatible with large and small parts, enable fast set-up and changeover for a wide variety of part shapes with low noise (OSHA noise limits are 90 dBa maximum employee exposure over eight hours). The part variety that the company selected for automation had random shapes and made upto 75% by volume of parts that need to be handled in the foundry plant.

2.1 Evaluating the suitability of available gripper solutions

Available rigid part handling grippers mentioned in the literature can be classified into the following:

2.1.1 Impactive Grippers

This is the most common type of gripper in use. It includes the two jaw gripper (fig 2) which mimics the human's thumb-index grip, the three jaw gripper which mimics the human's thumb-index-middle grip that is used for almost 90% of light domestic and manufacturing tasks, and multi-fingered grippers.

Fig. 2 Pivoting two jaw gripper at an aluminum foundry (left); Parallel three finger gripper (right)

Impactive grippers are application specific and do not work well with flat parts and parts where the gripper fingers cannot reach sufficiently around the sides. The parallel jaw gripper in wide industrial use, is inflexible and inefficient to meet requirements of handling assembly parts of different geometries and weights.

2.1.2 Vacuum Gripper

Pneumatic grippers have been developed because of their simplicity, cleanliness and cost-effectiveness. These grippers use vacuum cups and are employed mainly for handling large metal and glass sheets or light objects where only a single surface of the object is approachable. Some examples include the gripper developed by Warnecke [20] and Wright [3] that can handle soft materials such as eggs and those that use suction-based control for handling limp material without distortion, deformation and damage. Ease of implementation, gripping strength, and low cost makes the vacuum grippers the commonest Astrictive method used in robotics and automation. In its simplest manifestation, a flexible suction cup is forced against a surface. Air is expelled as the flexible polymer cup is compressed. This method of grasping is good for generally parts with flat surfaces.

Fig. 3 Vacuum gripper (left) for handling sand cores (right) for casting at the foundry

The vacuum grippers have limitations of costly air-conditioning, wear of the suction bellows and the effort for controlling the individual vacuum grippers. (Fig 3-left) Moreover, the air or vacuum feed lines have to be carried out variably due to the stroke of the entire vacuum gripper unit.

2.1.3 Passive Grippers

Universal passive grippers are mainly used for simple pick and place operations where positional accuracy is not required. An early snake like gripper by Hirose [21], employed a system of joints and pulleys with a single actuator. A few designs have envisioned systems where moveable jaws with highly compliant surfaces contact the object from two or more sides, partially enveloping and thus securing it. Schimdt et al. introduced the idea of attaching elastic bags loosely filled with granular material, such as small pellets or spheres, to the gripper jaws.[6] A similar idea was also put forth by Reinmuller et al. These bags conform to the shape of any object they press against and, by simply evacuating the gas inside, can be turned into rigid molds for lifting the object.

Brown et al. [22] revisited the idea of using granular material for a universal gripper and show that the gripping process could be controlled by a reversible jamming transition. This approach replaces individual fingers by a material or interface that upon contact molds itself around the object performing shape adaptation autonomously by the contacting material and without sensory feedback. The gripper (Fig 4) approximates the limit of a robotic hand with infinitely many degrees of freedom, which are actuated passively by contact with the surface of the object to be gripped and are locked in place by a single active element, a pump that evacuates the bag.

Though, this gripper has been shown to work well in simple manipulation tasks such as pouring water from glass, handle fragile targets like raw eggs, wooden hemispheres, LEDs, foam ear plugs, small flashlight lightbulbs and pyramid shaped objects, it doesn't seem to work with flat objects and objects with low area of contact. The magnitude of the holding force, is clearly influenced by the objects shape. The objects that could not be gripped are those in which the gripper membrane cannot reach sufficiently around the sides, and also for objects like hemispheres larger than half the size of the gripper, or for very soft objects like cotton balls. Although these grippers are so amazing and can ideally handle any kinds of part, at least in short term, active grippers are expensive, unreliable, and not a good fit for industrial use.

Fig. 4 Jamming gripper with the foundry parts

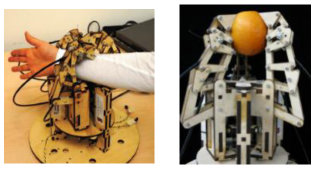


Fig. 5 Underactuated gripper

2.1.4 Underactuated mechanical grippers

Many underactuated grippers for robotics have been developed over the last 30 years. They aim to strike a balance between versatility and complexity, grasping a wide range of shapes and sizes while minimizing the number of actuators, simplifying control, and reducing the dependence on sensing. [21][22][23] In these hands, springs or compliant elements are often used to provide passive control over the order in which the finger joints grasp an object. The compromises associated with underactuation and the kinematics required to perform stable wrap grasps, however, generally limit the repertoire of available grasps. The efforts include the RTR II [22] and the Seabed Rig hand (Fig 5). Underactuated hands, which use the passive elements such as springs or mechanical limits, can obtain good grasping performance with shape adaptation. This approach, namely, *underactuation*, can be implemented through the use of passive elements like springs or mechanical limits leading to a mechanical adaptation of the finger to the shape of the object to be grasped. An underactuated hand mechanism that is able to adopt a wide range of grasp types by varying the internal forces in its fingers is shown in Fig 5.

The adjustment is accomplished by varying the preloads of springs, which affect the grasp stability and stiffness for large and small objects. Preload adjustment can be accomplished with low power, non-backdrivable actuators in the fingers. Adding a spring-preload mechanism to an underactuated finger leads to increased grasp stability across a wider range of objects than a single preload can achieve. In a simple finger this mechanism changes the effective grasping forces but does not change the grasp. In more complicated fingers, the same underlying principle can be used to change the locations and contact conditions of the grasp, leading to gross changes in posture, advantageous for grasping an even larger range of objects.

The robotic hand that is capable of changing its grasping style to accommodate both large and small objects. Changing the preload of internal springs changes the balance of internal forces, allowing the finger to adopt a range of poses between a wrap and pinch grasp. From a real world implementation perspective this gripper has high friction between the many moving parts, relatively expensive construction, and is unable to grasp flat parts. Very few underactuated hands have been applied to practical applications, because they would lead to slightly non-intuitive behaviors and produce non-stable grasping. [24]

2.1.5 Dextrous Hands

Many dexterous robot hands have been built over the past three decades. [7][8] Unfortunately, these dexterous hands cannot be controlled and built easily, and are expensive with many sensors and actuators. Most of them are still in laboratory stage and require much computing power and have not been used in industrial practice.

2.1.6 Magnetic Grippers

These have either electric or permanent magnets. Permanent magnets in the form of metal oxides (Fe_20_3) have existed since the Paleozoic. The first application is known in China around 2000 BC with compasses for direction orientation. In Europe, probably the Vikings were the first users magnets for navigation. A simple permanent magnet can be used to acquire ferrous objects. Specially designed magnets incorporate a mechanical switch mechanism for purposes of flux diversion. Typical retention pressures could be as high as 100-200KN/m^2 for specially designed permanent magnets. Permanent magnet grippers maintain their magnetic force almost indefinitely. The permanent magnets have the advantage of being operational even when an external power source is disconnected/power outage, unlike electromagnets.

One major problem with permanent magnets is that of remanence. Many magnetically susceptible materials remain slightly magnetized for a short while after field removal. A thin polymer coating on the magnetic surface of the gripper can reduce this problem significantly. An electromagnet consists of at least one pair of north and south magnetic poles that are separated by an airgap. In this way, there is practically no magnetic field present when a current flows through the coil, because air presents a very high reluctance to the magnetic flux. When a part is placed on the surface of the electromagnet in such a way that it connects a north and south pole, the magnetic flux can be established, given that the part is made of a ferromagnetic material. The magnetic flux will produce a force of attraction between the part and the electromagent. Two parts made of the same material and having the same geometry and dimensions could experience a different force of attraction on a given electromagnet if the contact conditions between the workpiece and the electromagnet are different for the two of them. Of one of the parts has a rougher surface or has a larger flatness error, the contact interface will have larger airgaps that have to be transversed by the magnetic flux in order to complete the magnetic circuit. Electromagnet grippers offer simple compact construction with no moving parts, uncomplicated energy supply, flexibility in holding complex parts and reduced number of set-ups, and are thus suitable to ferrous metalcasted parts. However, their use is limited to ferrous materials (Iron, Nickel, Cobalt), electromagnet size is directly dependent on required prehension force; residual magnetism in the part when handled when using DC supplies requires the additional of a demagnetizing operation to the manufacturing process.

In any automation task the requirements for the handling of the part has to be mapped carefully to select the optimal gripper solution. In cast part handling this becomes particularly important. Handling of casted parts does pose challenges with respect to mechanical handling and to health and safety. These challenges lead to conflicting requirement specifications. Some requirements will favour one gripping technology while others will rule out the same technology. A requirement list will then have to put weights on the different requirements in order to be able to satisfy the most important ones. Table 1 shows a subjective analysis from (best estimate) from the industrial observations at the case company and experience in the laboratory. The table has been composed with hazardous cast iron part handling challenges in mind. The classification is crude. A + indicates that the technology works well. The sign 0 indicates neither bad nor good, while − indicates unsuitability. For some factors, such as one sided grip and precise positioning with a universal passive gripper, the suitability is a go/no go issue. But for gripping on rather flat slight contoured surfaces the suitability may not be so clear.

Table 1. Qualitative performance parameters for different gripper types.

Gripper Type	Cast part with Flash	Flat Cast object	Sand Core	Single sided grip
Impactive Grippers	+/0	-/0	+	-
Vacuum Grippers	+/0	+	+	+
Passive Grippers	-/0	-/0	Not available	-
Permanent Magnet Grippers	+/0	+	-	+
Dextrous Hands	-/0	-	Not available	-
Electromagnetic Grippers	+/0	+	-	+

3. Industrial Implementation

Version I gripper

Four versions of grippers were developed. The first version of gripper developed is shown in Fig 6. This gripper works well in lifting small flat parts. The gripper consist of an off-the-shelf flat electromagnet ø60 mm, attached to the robot end via a pneumatic cylinder (Festo, DFM-20-40-B-PPV-A-GF, p_{max} = 10 bar). Gripper I is limited in its capabilities when handling complex parts with special contours. Hence there was a need to develop a specialized magnetic gripper to handle the pre-selected parts at the foundry.

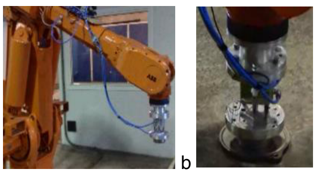


Fig 6 a.Version I gripper b.Gripper in use

Version II gripper

Version II weighs 25 kgs and has a pneumatic cylinder with stroke length 30mm (Rexroth ø63 H 30, 0822 010 875) on the top center, and range for the three arms is 100mm using linear step motor. The motivation for the design was to have a flexible gripper that could handle parts of size range 200mm-320mm. The length of the arms is 260mm (including 40mm height of ø80mm magnet) with a 3° compliance at the joint. Triangular workspace ranges from 350-500mm. Fig 7 shows the gripper working principle and the prototype in action. The limitation of this gripper is the fact that the flat ends of the electromagnets causes problems in picking curved profiles of cast iron parts produced by the company.

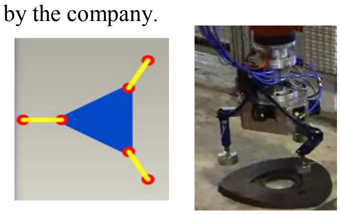


Fig. 7 a. Gripper working principle b. Prototype in Action

Version III gripper

This version of the gripper weighs 20 kgs has a stroke length of 150mm on the three sides of the gripper. The electromagnets move over a distance of 40mm and are attached via a pneumatic cylinder (Festo, DFM-20-40-B-PPV-A-GF, p_{max} = 10 bar) to the upper rails. Three servo motors 24 V (Faulhaber Minimotor SA) each, are used for the movement on the rails. The voltage used for the electromagnet is 24V DC. The main difference between the versions II and III is the workspace covered by the electromagnets and the types of electromagnets used. This gripper has a limitation while bin picking parts that are stacked towards the edges of the bin, as it may crash towards the edge of the bin. (Fig 8 and 9)

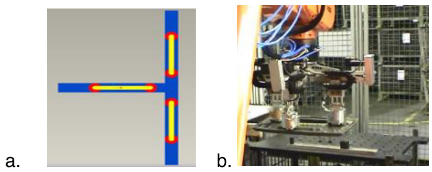


Fig 8 a. Gripper working principle b. Prototype in Action

Fig 9 Bin with part arrangement that creates potential gripper crash on the edges (shown by arrows)

Version IV gripper

The forth version (as shown in Fig 10) had incorporated custom made electromagnets (proprietary). The main advantage of version iv gripper when compared to the previous ones is its ability to reconfigure itself to pick parts of varying linear dimensions from both a conveyor belt, as well as the ability to pick parts from a bin and with special contours. The optimized dimensions for the base of the reconfigurable gripper were a length of 400mm, a width of 270mm and a height of 325mm from the robot gripper interface. Total weight of the gripper is roughly 35 kgs.

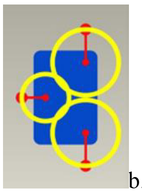
a.  b. 

Fig. 10. a. Gripping Principle b. Gripper designed and implemented at the flexible finishing cell

Implementation of solutions at the foundry finishing cell

The foundry wanted to look into automating the CNC finishing and thereby reducing the manual handling of heavy parts with flash on its edges. The manufacturing automation installation consists of the modules: (1) vision system, (2) robot module (3) the robot grippers (4) automated storage lift, (5) CNC machine (6) part family fixtures. When there is an order from ERP system to meet a request downstream at the foundry, the HMI requests the bin selection from storage lift. When the requested bin is available at the exit of the lift the robot receives a signal notifying that the bin is in place under the vision system. The position and orientation of the part/fixture is transferred to the robot via the PLC, which then proceeds to orient the gripper accordingly to pick the part. The part is loaded by the robot on the CNC. The delivery of the part on the CNC fixture is confirmed by the inductive sensors located on the fixture. The part is located on the fixture via rotation and sliding locators. A sliding locator ensures that the variation in part linear dimensions during the casting process is properly compensated. If the part is in the correct position the clamps are activated and the machining starts.

4. Summary and current work-in-progress

Research on the holding force of electromagnet grippers and cast iron parts is in its early stages. Many factors influence the force of attraction between the two and their effects are not well understood. The structure, defects and properties of the finished iron casting can impact the part handling automation capabilities. [26] The installation of the robot cell is fairly recent (lack of data); detailed investigation of additional mechanisms in action during industrial use is currently not available. Currently at the foundry, there are still many odd shaped parts such below, sizes ranging from 14cm x 26 cm x 14cm (length x width x height) weighing between 2-3 kgs that need automated handling. Painted and enamelled parts could be scratched by the electromagnet during handling. This necessitates for a soft yet strong hold gripper to handle such parts. A prototype was developed with an electromagnet surrounded by a vacuum suction gripper but the concept isn't currently tested at the foundry.

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